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DENDROCHRONOLOGICAL AND WOOD-ANATOMICAL FEATURES OF DIFFERENTLY VITAL PEDUNCULATE OAK (*QUERCUS ROBUR* L.) STANDS AND THEIR RESPONSE TO CLIMATE

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Abstract: *Quercus robur* dieback remained not completely explained even though numerous papers have been focused on this problem. In the future, more severe and unpredictable climate conditions are expected which may additionally accelerate oaks dieback. It is essential to understand the relationship between climate and tree growth to make proper management measures. Declining and vital group of pedunculate oaks from two sites in Slovenia were compared. Comparing to the group of vital trees, group of declining trees showed superior growth in earlier stage of development which may contribute to their higher vulnerability to environmental changes. Dieback of declining trees was at first visible in ring width (RW) and latewood width (LW). Only in 1995, when final stage of mortality started, smaller conductive elements were observed. Relationship between climate and analyzed parameters (ring width, earlywood width, latewood width, total vessel area, mean vessel area and maximal vessel area) was related to site specifications and was therefore considerable different for both groups. Vital trees from slightly hilly location were responding to the mean temperatures and sum of precipitations. Declining group from lowlands in Cigonca was corresponding only to the mean monthly temperatures.

Keywords: pedunculate oak (*Quercus robur* L.), dendroclimatology, oak dieback, wood anatomy, *Querco-Carpinetum*

DENDROHRONOLOŠKA I ANATOMSKA SVOJSTVA SASTOJINA LUŽNJAKA (QUERCUS ROBUR L.) RAZLIČITIH VITALNOSTI I NJIHOVA REAKCIJA NA KLIMU

Izvod: *Propadanje Quercus robur nije u potpunosti objašnjeno, iako su brojna istraživanja bila fokusirani na ovu temu. U budućnosti, očekuju se promena klimatskih uslova koji dodatno mogu da ubrzaju propadanje hrastova. Neophodno je da se razume odnos između klime i rasta drveća da bi se donele odgovarajuće mere upravljanja. Dve grupe hrastova (propadajući i vitalni) sa dve lokacije u Sloveniji su poređene. U odnosu na grupu vitalnih stabala, grupa propadajućih stabala se pokazala kao superiornija u rastu tokom rane faze*

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razvoja što je možda doprinelo njenoj većoj ranjivosti na promene u životnoj sredini. Propadanje stabala grupe koja je doživela mortalitet je prvo vidljivo u širini godova i širini kasnog drveta. Samo u 1995 godine, kada je počela završna faza umiranja, primećeni su uži provodni elementi. Odnos između klime i analiziranih parametara (širina godova, širine ranog drveta, širine kasnog drveta, srednje površine traheja i ukupne površine traheja) je u vezi sa specifičnostima lokaliteta i stoga se oni razlikuju kod obe grupe. Vitalna drveće na blago brdovitom terenu su reagovala na srednje temperature i sume padavina. Propadajuća grupa iz ravnice Cigonca su reagovale samo na srednje mesečne temperature.

INTRODUCTION

Forest degradation has been well discussed topic in the last decades. Among tree species, oaks showed great decrease in their vitality all over the Europe. Driving forces for oak decline in Slovenia have already been described; from air pollution (Šolar, 1977), water regime manipulations (Čater and Batič, 1999; Levanič et al., 2011), pathogenic fungus (Sedlar, 2009) to insect outbreaks (Kelenc, 2008; Komanjc, 2009). Our research was focused on differences between two differently vital groups of pedunculate oaks (*Quercus robur*) from two closely related sites in Slovenia and their response to climate.

Dendrochronological approach enables us to investigate the historical development of tree parameters and their relationship to changes in their environment. Levanič et al., (2011) explained different mortality rate in pedunculate oaks from lowlands in Cigonca with differences in growth parameters in early stage of development. Trees that were almost dead at the time of sampling had significantly wider conductive elements and tree ring widths in earlier stages of development. Čater et al., (2008) determined differences between differently vital pedunculate oaks in pre-dawn water potential (PWP), radial growth and available nutrients. Stojanović et al., (2015) connected air temperatures and water level of Sava River with growth indices of pedunculate oak in Srem (Srbija). The water level and temperature changes caused oak forest decline in last 30 years. Similarly, oak dieback was also related to decreased water level of Danube River in Northern Serbia (Stojanović et al., 2014). However, there is a lack of comparison between differently affected oaks and wood-anatomical parameters. In a recent decade, great step forward has been done in the area focused on developing wood-anatomical proxy records (for a review see Fonti et al., 2010).

Environmental changes are one of the most challenging and crucial problems of the mankind. Oaks dieback has already been linked to extreme climate conditions (e.g. Pryzbylova, 1989; Rösel and Reuther, 1995; Hartmann et al., 1989). Therefore it is essential to understand the relationship between climate and forest growth.

Our goal is (1) to estimate the differences in dendrochronological and wood-anatomical parameters between differently affected groups of oaks and (2) to determine the relationship between dendrochronological and wood-anatomical parameters and climate.

MATERIALS AND METHODS

Study objects

Two study objects were included in our research. In study object Mlače (46°18′21.43″N, 15°30′35.43″E) vital trees were sampled. Plot is located at 300 m elevation, association is determined as *Querco-Carpinetum luzuletosum*. Surface is uneven on slightly hilly location; soil type is eutric brown soil on marl. Second research object is Cigonca (46°21′51.49″N, 15°34′44.75″E) where declining trees were sampled. Cigonca is located on a flat surface at elevation 265 m. Association is classified as *Querco–roboris carpinetum*. Surface in Cigonca is plane, soil type is deep, seasonally saturated and strongly gleyed (amphigleys) on alluvial loams. In 1982 large-scale drainage manipulations happened on nearby farmland, and soon afterwards a dieback of nearby forest was observed. Both forest stands are even aged, germinated in 1860 (Mlače) and 1870 (Cigonca).

Climate data

We received climate data from Slovene Environmental Agency (ARSO). Temperature data for Maribor were extended back in time till 1900 using data from Ljubljana and spatial linear interpolation. Overlapping years were from 1961 till 2012. Using the same principle we tried to extend also precipitation data for Slovenske Konjice, but due to high spatial variability of precipitation in Slovenia the unexplained variance was too high to produce meaningful result. Therefore only data from 1961 till 2012 for monthly precipitation were used in analysis.

Sampling methods

Vital trees from Mlače were cored in October 2012. From 12 trees we took 24 cores (2 per tree) at the breast height (1.30 m), from which 18 were 5 mm thick and 6 of them were 12 mm thick and later used in wood-anatomical analysis. 5 cross sections from Cigonca were collected in 2004. All 5 sampled trees showed clear signs of ensuing mortality.

Dendrochronological analysis

Samples were air dried and sanded to a high polish in the laboratory. Digital images were taken with ATRICS system (Levanič, 2007) and later used for measurements of ring widths (RW), earlywood (EW) and latewood widths (LW) with WinDendro. Final synchronization was done in PAST-4. With COFECHA the quality of measurements and eventual mistakes were checked. RW and LW chronologies were standardized using ARSTAN. Modified negative exponential function was used to remove non-climate factors. In further analysis standardized chronologies were used.

Wood-anatomical analysis

5 samples from Cigonca and 6 samples from Mlače were used in wood-anatomical analysis. High quality images were analyzed with ImageJ program using macro EWVA (Jevšenak and Levanič, 2014). Macro EWVA was developed as a free alternative to highly specialized and payable software for analyzing earlywood conduits. Our macro enables automatized recognition of earlywood and effective analysis of vessels of ring porous species. Macro is presented in the paper Jevšenak and Levanič, (2014) it is free and could be provided by contacting the authors.

After measurements the following parameters were calculated using R program: total vessel area (TVA), mean vessel area (MVA), and maximal vessel area (MxVA) which included only the biggest vessel from each annual ring. The smallest vessel area included in analysis was set as 0.01 mm^2.

RESULTS

Dendrochronological and wood-anatomical parameters

The differences between vital and declining trees were determined in diameter increment and wood-anatomical features. Declining group showed higher RW, EW and LW in earlier stages of development. Vital group showed the tendency of increasing RW, EW and LW, while declining group showed the tendency of decreasing values (Figure 1). Obvious collapse in values of RW and LW of declining trees is visible in year 1982 (Figure 1), when large-scale drainage manipulations happened on nearby farmland.

Wood-anatomical analysis additionally explained differences in vitality and growing patterns. Declining group from lowlands had constantly higher values in MVA and MxVA till 1995, when all the values for declining group drastically dropped (Figure 2b and 2c). Parameter TVA started to drop in 1982, but more obvious decline also happened in 1996 (Figure 2a). Parallel behavior of chronologies from both sites is more obvious in the years before dieback in Cigonca.

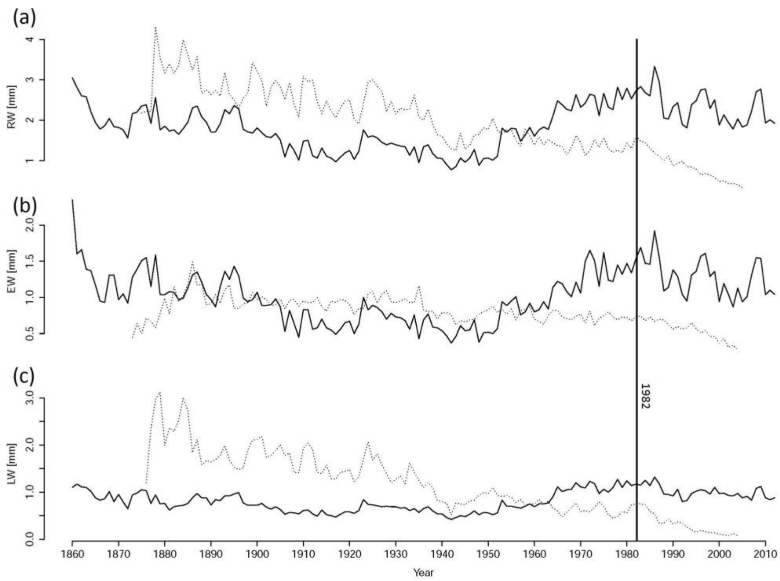

Figure 1. Tree-ring widths (a), earlywood widths (b) and latewood widths (c) of declining (dotted line) and vital (full line) trees.

Slika 1. *Širine prstenova (a), širine ranog drveta (b) i širine kasnog drveta (c) kod odumirućih (tačkasta linija) i vitalnih (puna linija) stabala*

Climate signal

Cigonca

Relationship between climate and growth parameters shows which climate variables are limiting factors in specific forest stands. Declining group from lowlands is significantly responsive only to the mean monthly temperatures. Dendrochronological parameters of declining group are responsive mostly to the temperatures in August of the current year. In general, spring and summer temperatures seem to have the highest influence on parameter values in Cigonca. Based on seasonal values, LW showed slightly stronger connection to temperatures than RW, but the highest linkage to climate showed EW which was also significantly correlated to the temperatures at the end of the previous growing season. All significant correlation coefficients were strictly negative. Significant correlations between chronologies from declining group and monthly precipitation were not found (Table 1).

In general, wood-anatomical parameters showed higher dependence on temperatures for declining group. The highest linkage showed TVA which values are strongly correlated to the temperatures at the end of previous growing season and also at the time of current growing season. Similar pattern showed also MVA and MxVA but with smaller and less significant correlation coefficients (Table 1).

The only significant correlation with the monthly precipitation was found for June of the current growing season.

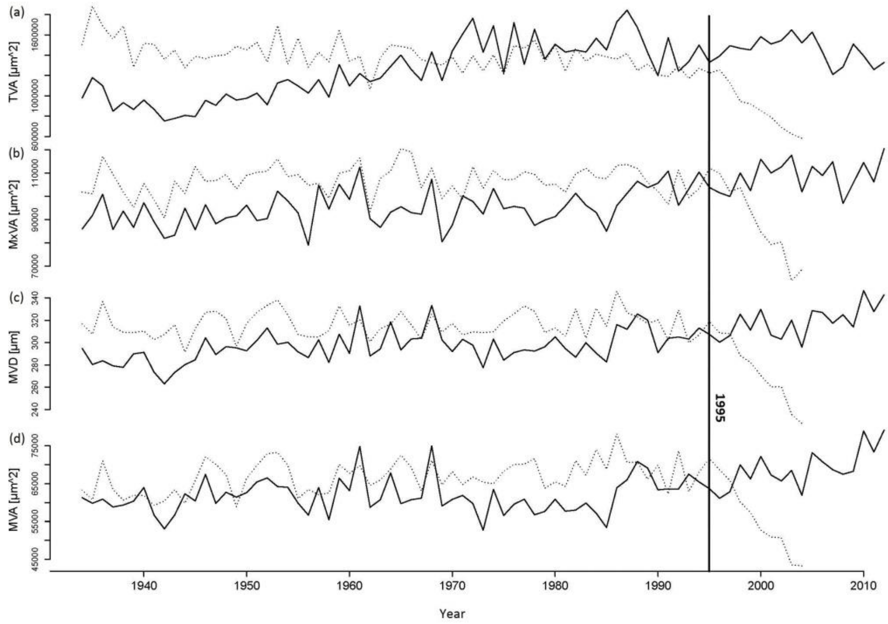

Figure 2. Total vessel area (TVA), mean vessel area (MVA) and maximal vessel area (MxVA) for vital (full line) and declining group (dotted line) for period 1934 – 2012(2004). Declining group had bigger conductive elements till the 1995 when final mortality stage started.

Slika 2. *Ukupna površina snopića (TVA), srednja površina snopića (MVA) i maksimalna površina snopića (MxVA) za vitalnu (puna linija) i odumiruću grupu (istačkana linija) za period 1934-2012(2004).Odumiruća grupa je imala veće sprovodne elemente do 1995 kada je počela finalna faza odumiranja*

Mlače

Vital group is responsive to the mean temperatures and sum of precipitations. Mean July temperature has the strongest influence on RW and LW. RW and LW capture climate signal to a similar extent. The highest correlation was found between RW and June precipitation. All significant correlation coefficients in Mlače are positive (Table 1).

Wood-anatomical parameters showed higher responsive rate to the temperatures than RW, EW and LW. The highest correlation value for a single month was calculated for April ($r = 0.60$) for parameter MVA. Also temperatures at the end of the previous growing season; in July and August showed significant positive influence on conductive elements (Table 1).

Table 1. Correlation coefficients (r) between environmental variables and dendrochronological parameters*
Tabela 1. *Korelacioni koeficijenti (r) između klimatskih promenljivih i dendrohronoloških parametara**

		WOOD-ANATOMICAL PARAMETERS *ANATOMSKI PARAMETRI*												DENDROCHRONOLOGICAL PARAMETERS *DENDROHRONOLOŠKI PARAMETRI*											
		TEMPERATURES *TEMPERATURE*						PRECIPITATION *PADAVINE*						TEMPERATURES *TEMPERATURE*						PRECIPITATION *PADAVINE*					
		Vital *Vitalna*			Declining *Odumiruća*			Vital *Vitalna*			Declining *Odumiruća*			Vital *Vitalna*			Declining *Odumiruća*			Vital *Vitalna*			Declining *Odumiruća*		
		TVA	MVA	MxVA	TVA	MVA	MxVA	TVA	MVA	MxVA	TVA	MVA	MxVA	RW	EW	LW	RW	EW	LW	RW	EW	LW	RW	EW	LW
PGS	Jul	0.27	**0.46**	**0.48**	-0.27									0.28	0.21	**0.30**		-0.23							
	Aug	0.33	**0.47**	**0.50**	**-0.57**	-0.29	-0.36							0.29	0.23	0.28	-0.29	**-0.47**							
	Sep		**0.36**	0.23																					
	Oct		0.28	**0.38**	-0.25		-0.24							0.27	0.19	**0.33**									
Growing season *Vegetacioni period*	Jan	0.27		0.33					**-0.33**	-0.29				0.19	0.22										
	Feb		0.23	0.34						-0.32								-0.21		0.28		0.32			
	Mar		**0.36**	**0.51**						-0.32							-0.21	-0.27							
	Apr		**0.60**	**0.39**	-0.24												-0.23	**-0.30**							
	May		0.29	0.31	**-0.48**		-0.26							0.21	0.21			**-0.34**	-0.20						
	Jun		**0.47**	**0.50**	-0.32	-0.33	-0.34						0.31				-0.30	-0.27	**-0.36**	**0.51**	**0.47**				
	Jul	-	-	-	-	-	-	-	-	-	-	-	-	0.29	0.22	0.29		-0.22	-0.21						
	Aug	-	-	-	-	-	-	-	-	-	-	-	-	0.23	0.22	0.22	**-0.35**	**-0.52**	**-0.32**						

Labels: wood-anatomical parameters: total vessel area (TVA), mean vessel area (MVA) and maximal vessel area (MxVA); dendrochronological parameters: ring-width (RW), earlywood width (EW), latewood width (LW). Previous growing season (PGS). Correlation coefficients with $p \leq 0.05$ are displayed; bold coefficients have $p \leq 0.001$.
Oznake: anatomski parametri: ukupna površuna snopića (TVA), srednja površina snopića (MVA), mksimlna površina snopića (MxVA); dendrohronološki parametri: širina prstena (RW), širina ranog drveta (EW), širina kasnog drveta (LW). Prethodni vegetacioni period (PGS). Predstavljeni su koeficijenti korelacije sa $p \leq 0.05$*; podebljani koeficijenti imaju* $p \leq 0.001$.

Sum of precipitation in January has a negative effect on MVA and MxVA. The impact of winter and spring precipitation on TVA is insignificant (Table 1).

DISCUSSION

Before onset of growth decline, declining group had a higher growth rate and larger conductive elements in comparison to the vital group from Mlače. Despite the minor differences in soil type and slope between sites Mlače and Cigonca, our finding from Mlače are in accordance with Levanič et al., (2011) where faster growing trees from Cigonca in younger stages showed higher vulnerability to droughts in later developmental stages. Some authors (e.g. Tyree and Zimmerman, 2002; Hacke and Sperry, 2001; Cochard, 2006) concluded that bigger conductive elements are more likely to be effected by cavitation, which could also help explaining mortality of oaks from Cigonca.

Large-scale drainage manipulations in 1982 and afterwards a decrease in the groundwater table caused dieback of oaks in Cigonca. Čater and Batič, (1999) also confirmed relationship between ground water table and degree of vitality. Physiologically weakened and with water less supplied trees are more likely to succumb to stressful ecological factors (Čater and Batič, 1999). The consequences of drainage manipulations were at first visible in RW, LW and TVA. Only in 1995 signs of dieback were visible in a decreasing dimensions of conductive elements. It seems like trees compensated their reduced vitality mostly by reducing LW, RW and dimensions of the conductive tissues. Conductive elements, in particular, are vital for survival since they supply all parts of the tree with water and minerals and tree will maintain its vessels using different survival strategies, one of them is also reduction of size, in our case, this happened after 1995. No extreme climate conditions were reported in years around 1995.

Understanding limiting factors may help us to explain oak dieback and to predict the future vitality in relation to the environmental changes. Tree parameters from both sites were correlated with average monthly temperatures, while trees from Mlače were additionally correlated to monthly sum of precipitation. Wood-anatomical parameters showed higher correlation to temperature for vital group than RW, EW and LW. However, declining group from Cigonca showed somehow similar degree of connection between temperatures and both types of parameters. We assume those differences are site-specific and could not be generalized.

In Cigonca negative influence of above average temperature on RW, EW, LW and wood-anatomical parameters was observed, but this phenomenon has to be interpreted with caution, since temperatures have increasing trend and growth parameters are decreasing. This could be causing false correlations. In fact, additional analyses confirmed our speculations.

EW and wood-anatomical parameters showed significant correlations with temperatures at the end of the previous growing season. This dependence is usually linked to oaks characteristic to start EW production before bud breaks (Wareing, 1951; Aloni, 1995), although some novel papers (Sass-Klassen et al., 2011) put doubts on that well accepted fact.

Dimensions of the conductive elements from both sites are slightly more dependent on temperatures at the time of their formation than on temperatures at the end of the previous growing season. Similar findings were reported from Matisons and Dauškane, (2009). Sum of precipitation at the end of the previous growing season did not show any influence on conductive elements. Many authors claim the strongest climate signal for oak species comes from LW (e.g. Eckstein and Schmidt, 1974; Zhang, 1997; Nola, 1996). However, our research did not confirm those findings. Declining group had the strongest climate signal in EW, while vital group captured climate signal mostly in RW and LW.

Some high correlations, like dependence between summer temperature and EW, are difficult to explain (e.g.). Recent research showed that last earlywood vessels in oak are produced in May (Gričar, 2008; Sass-Klaassen et al., 2011). Thus having a high correlations between earlywood vessels and summer temperature could be statistical artefact or could be related to multicollinearity among dendrochronological and wood-anatomical parameters (Tardif and Conciatori, 2006).

CONCLUSIONS

Declining and vital group of pedunculate oaks from two *Querco-Carpinetum* sites in Slovenia showed different growth characteristics in earlier stage of development. Declining group had higher growth rate and larger conductive elements in comparison to vital group from Mlače. Superior growth in earlier stages of development may contribute to higher vulnerability to environmental changes. Water regime changed in 1982 was at first visible in reduced RW and LW. EW and TVA showed only slightly decreasing values which were constantly dropping till the 2004. MVA and MxVA showed tree mortality only in 1995. Reduced vitality was therefore not compensated with smaller conductive elements. Both sites showed different response to climate variables. Response to climate is more related to site specifications than to tree species. We believe groundwater table should be more often taken into an account. Negative influence of precipitation on vessel size in Mlače could be better understood with wood anatomical research accompanied with precise daily climate data. Negative influence of temperatures on all analyzed parameters in Cigonca is caused by the opposite trends of increasing temperatures and decreasing growth variables connected with the dieback.

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Rezime

DENDROHRONOLOŠKA I ANATOMSKA SVOJSTVA SASTOJINA LUŽNJAKA (QUERCUS ROBUR L.) RAZLIČITIH VITALNOSTI I NJIHOVA REAKCIJA NA KLIMU

od

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Propadajuća i vitalna grupa hrasta iz dve Querco-Carpinetum sastojine u Sloveniji pokazali su različite karakteristike rasta u ranijoj fazi razvoja. Propadajuća grupa imala je veću stopu prirasta i veće provodljive elemente u odnosu na vitalnu grupu iz Mlača. Brži rast u ranijoj fazi razvoja može da doprinese većoj ranjivosti na promene u životnoj sredini. Promena režima voda 1982. godine je prvo bila vidljiva u smanjenoj širini godova i širini kasnog drveta. Rano drvo i površina traheja pokazali su blago opadanje koja ja nastavljena sve do 2004. Prosečna i maksimalna površina traheja je ukazala da će doći do mortaliteta stabala nakon 1995. godine. Smanjena vitalnost stoga nije mogla biti kompenzovana sa manjim provodljivim elementima. Obe sastojine su pokazale drugačiji odgovor na klimatske promenljive. Odgovor na klimu je bio u vezi sa specifičnostima lokaliteta. Verujemo da nivo podzemnih voda treba dodatno razmotriti. Negativan uticaj padavina na veličinu traheja na lokalitetu Mlače bi se bolje mogao razumeti dopunom ksilogenetskim istraživanjima u kombinaciji sa preciznim dnevnim klimatskim podacima. Negativan uticaj temperature na sve analizirane parametare lokaliteta Cigonca je uzrokovan suprotnim tendencijama povećanja temperature i smanjenja prirasta zbog propadanja.